

# HELAC-PHEGAS: a generator for all parton level processes

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<http://www.cern.ch/helac-phegas>

## Abstract

The updated version of the HELAC-PHEGAS event generator is presented. The matrix elements are calculated through Dyson-Schwinger recursive equations using color connection representation. Phase-space generation is based on a multichannel approach, including optimization. HELAC-PHEGAS generates parton level events with all necessary information, in the most recent Les Houches Accord format, for the study of *any process* within the Standard Model in hadron and lepton colliders.

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## Program summary

*Program Title:* HELAC-PHEGAS

*Journal Reference:*

*Catalogue identifier:*

*Licensing provisions:* none

*Program obtainable from:* <http://helac-phegas.web.cern.ch/helac-phegas/>

*Distributed format:* tar gzip file

*Programming language:* FORTRAN

*Computer:* All

*Operating system:* Linux

*Keywords:* Dyson-Schwinger equations, recursive algorithms, automatic evaluation of helicity amplitudes and total cross sections.

*PACS:* 12.38.Bx, 13.85.Dz, 13.85.Lg

*Classification:* 11.1, 11.2

*External routines/libraries:* Optionally Les Houches Accord (LHA) PDF Interface library.

*Nature of problem:* One of the most striking features of final states in current and future colliders is the large number of events with several jets. Being able to predict their features is essential. To achieve this, the calculations need to describe as accurately as possible the full matrix elements for the underlying hard processes. Even at leading order, perturbation theory based on Feynman graphs runs into computational problems, since the number of graphs contributing to the amplitude grows as  $n!$ .

*Solution method:* Recursive algorithms based on Dyson-Schwinger equations have been developed recently in order to overcome the computational obstacles. The calculation of the amplitude, using Dyson-Schwinger recursive equations, results in a computational cost growing asymptotically as  $3^n$ , where  $n$  is the number of particles involved in the process. Off-shell subamplitudes are introduced, for which a recursion relation has been obtained allowing to express an  $n$ -particle amplitude in terms of subamplitudes, with 1-, 2-, ... up to  $(n - 1)$  particles. The color connection representation is used in order to treat amplitudes involving colored particles. In the present version HELAC-PHEGAS can be used to efficiently obtain helicity amplitudes, total cross sections, parton-level event samples in LHA format, for arbitrary multiparticle processes in the Standard Model in leptonic,  $p\bar{p}$  and  $pp$  collisions.

*Does the new version supersede the previous version:* yes, partly

*Reasons for the new version:* substantial improvements, major functionality upgrade

*Summary of revisions:* color connection representation, efficient integration over PDF via the PARNI algorithm, interface to LHAPDF, parton level events generated in the most recent LHA format,  $k_\perp$  reweighting for Parton Shower matching, numerical predictions for amplitudes for arbitrary processes for phase space points provided by the user, new user interface and the possibility to run over computer clusters.

*Running time:* Depending on the process studied. Usually from seconds to hours.

*References:*

- [1] A. Kanaki, C. G. Papadopoulos, Comput. Phys. Commun. **132** (2000) 306
- [2] C. G. Papadopoulos, Comput. Phys. Commun. **137** (2001) 247

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# 1 Introduction

Current and forthcoming high energy colliders allow the study of final states with many hard and well separated jets as well as charged leptons. These multiparton final states carry the signature of the decay of massive particles, such as for example W and Z gauge bosons, top quarks, Higgs bosons, and possibly supersymmetric particles, as well as the effect of new interactions. Therefore the accurate description of such processes is of fundamental importance for the study of the properties of the Standard Model particles as well as for the discovery of new physics.

Multiparton processes can be described within standard perturbation theory. At the leading order (LO) one needs to calculate matrix elements and efficiently integrate them over the available phase space. Although the procedure is well defined and straightforward in principle, several challenges are present in practice. First of all, if the matrix elements are calculated using the standard Feynman diagrams, the number of which grows factorially with the number of partons in the process, the set up of an efficient calculational framework in the multiparton case becomes impossible. The solution to this problem is by now well known and relies on the use of recursive equations instead of Feynman graph expansion [1–14]. HELAC [9, 10] has been the first implementation of the algorithm based on Dyson-Schwinger equations. It is able to calculate matrix elements for arbitrary scattering processes. A fundamental issue is the consistent inclusion of all color configurations within QCD for processes with colored partons. The color connection representation is used in HELAC, and the programme is actually able to calculate all possible color connections for arbitrary processes. For amplitudes with many colored particles, a Monte-Carlo treatment over color should also be used. This issue has also been addressed so far in references [8, 11]. Moreover, a new version of the HELAC algorithm [12], based on explicit color configurations, has been proved very efficient in dealing with processes with many colored partons. The next challenge is the phase space integration. For the phase-space generation, PHEGAS [15] has been the first implementation of a complete automated algorithm of multichannel phase space mappings for arbitrary number of external particles. It uses information generated by HELAC and automatically performs a multichannel phase space generation, utilizing all ‘scalarized’ Feynman graphs, for any given process, as phase space mappings. Finally, since colliding particles like protons are not elementary one has to take into account a number of elementary parton level subprocesses.

It should be mentioned that a number of computer programs, like for example ALPGEN [17, 18], [19], MADEVENT [20–22] SHERPA [23, 24], WHIZARD [25] are available, which implement some of these techniques and can be used to obtain leading order predictions for processes with a rather high number of final state particles.

In the present paper we will summarize the new developments in the HELAC-PHEGAS which fall into two categories:

## 1. **Functionality:**

- (a) Full implementation of QCD in the color connection representation
- (b) Automatic summation over subprocesses for  $pp$  and  $p\bar{p}$  colliders and  $e^+e^-$  colliders
- (c) Built-in CTEQ611 PDF support [26,27] with alternative interface to the LHAPDF library [28]
- (d)  $k_T$  reweighting for matching algorithm to parton shower programs, e.g. PYTHIA [29,30], HERWIG [31] or HERWIG++ [32]
- (e) Parton-level event files in the LHA format [33,34]
- (f) Extended set of standard cuts

## 2. User interface:

- (a) Program control using a single user input file managed by scripts
- (b) Easy access to numerical amplitude values for a user given phase space point
- (c) Set up for parallel runs on computer clusters

The present paper is organized as follows. In the next section, after a brief summary of the PHEGAS phase space generator and the HELAC algorithm, we describe the treatment of the color degrees of freedom, based on the color connection representation and the matching to the parton shower algorithms. The rest of the publication describes in detail the usage of the program. We summarize with a short outlook.

## 2 The HELAC-PHEGAS Algorithm

The core of HELAC-PHEGAS is made of a phase space generator and a matrix element evaluator. The algorithms of both have already been described previously in [15] and [9] respectively. Therefore, we will only give here a very short overview of the main ideas.

### 2.1 PHEGAS - Phase Space Generation

PHEGAS [15], is a multichannel self optimizing phase space generator. It automatically constructs all possible phase-space mappings in order to optimally describe the peaking structures of a given scattering process. These phase-space mappings, called also *channels*, have a one-to-one correspondence to the Feynman diagrams contributing to the given process. The information concerning the pole structure of all Feynman diagrams is produced by HELAC by using the skeleton construction of the solution of the Dyson-Schwinger recursive equations. The self-optimization is performed according to the ideas presented in [16]. Moreover since in several practical applications the number of phase-space channels may become quite large (of the order of many thousands), optimization

may be used to significantly reduce this number, based on the contribution of the corresponding channels to the total variance. At the end a few tens of channels are kept only, which is usually sufficient to give an adequate phase space efficiency. Let us stress that the selection of these channels is done automatically by the optimization procedure.

In the case of  $pp$  and  $p\bar{p}$  collisions, besides phase space generation for a given center-of-mass energy, an integration over the fractions  $x_1$  and  $x_2$  of the momenta of the initial partons, weighted by the parton distribution functions, is necessary. This integration is optimized via the PARNI algorithm [35]. Its efficiency has been proven to be very good.

## 2.2 HELAC - Amplitude Computation

HELAC uses an alternative [6–8,11] to the Feynman graph representation of the scattering amplitude which is provided by the Dyson-Schwinger approach [9].

Dyson-Schwinger equations express recursively the  $n$ -point Green's functions in terms of the 1-, 2-, ...,  $(n-1)$ -point functions. For instance in QED these equations can be written as follows:

$$\text{wavy line with circle} = \text{wavy line} + \text{wavy line with fermion loop}$$

$$b^\mu(P) = \sum_{i=1}^n \delta_{P=p_i} b^\mu(p_i) + \sum_{P=P_1+P_2} (ig) \Pi_\nu^\mu \bar{\psi}(P_2) \gamma^\nu \psi(P_1) \epsilon(P_1, P_2)$$

where

$$b_\mu(P) = \text{wavy line with circle} \quad \psi(P) = \text{fermion line with circle} \quad \bar{\psi}(P) = \text{antifermion line with circle}$$

describes a generic  $n$ -point Green's function with respectively one outgoing photon, fermion or antifermion leg carrying momentum  $P$ .  $\Pi_{\mu\nu}$  stands for the boson propagator and  $\epsilon$  takes into account the sign due to fermion antisymmetrization.

The computational cost of HELAC-PHEGAS's algorithm grows as  $\sim 3^n$ , which essentially counts the steps used to solve the recursive equations. Obviously for large  $n$  there is a tremendous saving of computational time, compared to the  $n!$  growth of the Feynman graph approach.

HELAC-PHEGAS is using a *top-down approach* in solving the recursive equations. In the first phase, a skeleton is constructed, composed by a series of vertices that are participating in the given amplitude. All this information is encoded using integer arithmetic. Then this information is used in order to actually calculate the amplitude. In this second phase, momenta from PHEGAS are used to compute wave functions. Based on the skeleton information the subamplitudes are computed using floating arithmetic. The result is the value of the matrix element for each given helicity and color connection configuration.

## 2.3 Color representation

The treatment of the color degrees of freedom is a very important issue, especially for amplitudes involving many colored particles. In the most commonly used approach we can express a  $n$ -gluon amplitude in terms of the so-called color-ordered amplitudes, using the following equation,

$$\mathcal{M}^{a_1 a_2 \dots a_n} = \sum_{\sigma} \text{Tr}(T^{a_{\sigma_1}} \dots T^{a_{\sigma_n}}) \mathcal{A}_{\sigma} \quad (1)$$

$\sigma = (\sigma_1, \sigma_2, \dots, \sigma_n)$  is permutation of  $(1, 2, \dots, n)$ . The sum is extended over all  $(n-1)!$  permutations, where  $\mathcal{A}_{\sigma}$  are functions of momenta and helicities of the external particles. The important thing is that these  $\mathcal{A}_{\sigma}$  color-ordered amplitudes can be calculated using the so-called color-ordered Feynman rules. In the framework of the Berends-Giele recursive equations, which is the Dyson-Schwinger equations subject to the restriction of ordering of the external particles (according to the permutation  $\sigma$ ), the computational cost grows like  $n^4$ , exhibiting a polynomial growth. When calculating the full color-summed matrix element squared, all  $(n-1)!$  terms have to be computed. This approach is some times referred as the *SU(N<sub>c</sub>) approach*. The inclusion of quark-antiquark pairs is possible, but the analogue of Eq.(1) becomes more complicated.

The *color connection representation* is based on a  $U(N_c)$  representation of the fields. In that case amplitudes involving quarks and gluons can be described in a unified way. To this end all indices of the adjoint representation are transformed to indices in the fundamental representation by multiplying with  $t_{i,j}^a$ ,

$$\mathcal{M}_{j_1 j_2 \dots j_n}^{i_1 i_2 \dots i_n} = \sum_a \mathcal{M}^{a_1 a_2 \dots a_n} t_{i_1 j_1}^{a_1} \dots t_{i_n j_n}^{a_n}. \quad (2)$$

When quarks are only involved no action is required. The  $U(N_c)$  representation has been introduced in Ref. [36]. It has been used in connection with matrix element evaluation in HELAC-PHEGAS [9, 10]. A Lagrangian based approach has also been used in [37].

Now the amplitudes can be written as follows:

$$\mathcal{M}_{j_1 j_2 \dots j_n}^{i_1 i_2 \dots i_n} = \sum_{\sigma} \delta_{i_{\sigma_1} j_1} \delta_{i_{\sigma_2} j_2} \dots \delta_{i_{\sigma_n} j_n} \mathcal{A}_{\sigma}. \quad (3)$$

In the above expression we have chosen to fix the order of anti-color indices. Without altering the result, the same can be done with the color indices. We have kept the same notation for the functions  $\mathcal{A}_{\sigma}$  in Eq.(1) and Eq.(3). This is indeed the case for the  $n$ -gluon amplitude but not when quarks are involved. In this representation there is no distinction anymore between gluons and quarks. Gluons are represented by a pair of color-anti-color lines, where quarks (anti-quarks) are represented by color (anti-color) lines. The number of permutations is in principle equal to  $n_l!$ , where  $n_l$  is the number of color (anti-color) lines. In a process with  $n_g$  gluons and  $n_q$  quarks (and  $n_q$  anti-quarks),  $n_l = n_g + n_q$ .

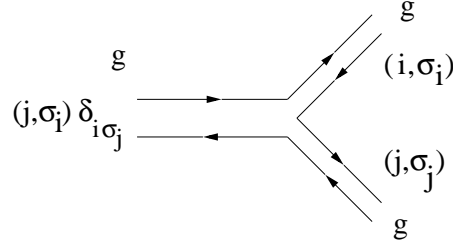
The important thing is again that the  $\mathcal{A}_{\sigma}$  function can be calculated using a given set of Feynman rules. For instance, the three-gluon vertex can be rewritten as

$$\sum f^{abc} t_{AB}^a t_{CD}^b t_{EF}^c = -\frac{i}{4} (\delta_{AD} \delta_{CF} \delta_{EB} - \delta_{AF} \delta_{CB} \delta_{ED}) \quad (4)$$

where on the right hand side only products of  $\delta$ 's appear. Let us introduce a more compact notation and associate to each gluon a label  $(i, \sigma_i)$ , which refers to the corresponding color index of the previous equation, namely  $1 \rightarrow A$ ,  $\sigma_1 \rightarrow B$  and so on. The use of  $\sigma_i$  labels will become clear in a moment. With this notation, the first term of the above equation is proportional to

$$\delta_{1\sigma_2} \delta_{2\sigma_3} \delta_{3\sigma_1} \quad (5)$$

and its diagrammatic representation is given by



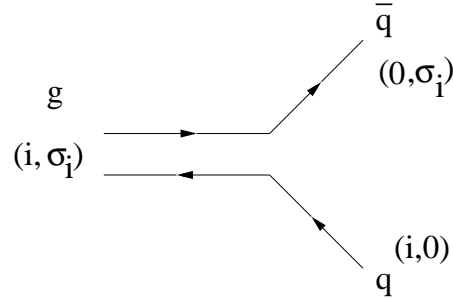
The momentum part of the vertex is still the usual one,

$$g_{12} (p_1 - p_2)^3 + g_{23} (p_2 - p_3)^1 + g_{31} (p_3 - p_1)^2 \quad (6)$$

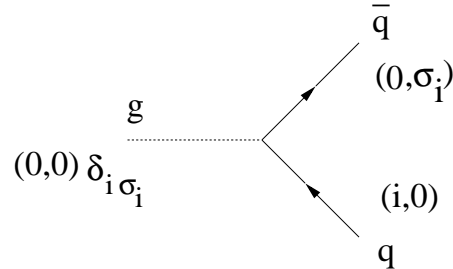
where  $g_{12}$  stands for  $g_{\mu_1\mu_2}$ , etc. For the  $q\bar{q}g$  vertex we have

$$\sum t_{AB}^a t_{CD}^a = \frac{1}{2} (\delta_{AD} \delta_{CB} - \frac{1}{N_c} \delta_{AB} \delta_{CD}) \quad (7)$$

and if we associate a label  $(i, 0)((0, \sigma_i))$  to a quark(antiquark) we have two possible vertices



as well as the one with the 'neutral' gluon, namely,



the last one with an extra factor proportional to  $i/\sqrt{N_c}$ . Finally the four-gluon vertex is given by a color factor proportional to

$$\delta_{1\sigma_3} \delta_{3\sigma_2} \delta_{2\sigma_4} \delta_{4\sigma_1} \quad (8)$$



and a Lorentz part

$$2g_{12}g_{34} - g_{13}g_{24} - g_{14}g_{23} \quad (9)$$

To make use of the color representation described so far, let us assign a label  $(i, \sigma_I(i))$  to each external gluon,  $(i, 0)$  to a (incoming) quark and  $(0, \sigma_I(i))$  to an (incoming) antiquark, where  $i = 1 \dots n_l$  and  $\sigma_I, I = 1 \dots n_l!$  being a permutation of  $\{1 \dots n_l\}$ . It is clear that since all elementary color factors appearing in the color decomposition of the vertices are proportional to  $\delta$ -symbols, the total color factor can only be given by

$$\mathcal{F}_I = \delta_{1\sigma_I(1)} \delta_{2\sigma_I(2)} \dots \delta_{n\sigma_I(n)} \quad (10)$$

Moreover the color matrix, defined as

$$\mathcal{C}_{IJ} = \sum_{\text{colours}} \mathcal{F}_I \mathcal{F}_J^\dagger \quad (11)$$

with the summation running over all colors,  $1 \dots N_c$ , has a very simple representation

$$\mathcal{C}_{IJ} = (N_c)^{m(\sigma_I, \sigma_J)} \quad (12)$$

where  $1 \leq m(\sigma_I, \sigma_J) \leq n$  counts the number of cycles made by the elements of the permutations  $\sigma_I$  and  $\sigma_J$ .

The practical implementation of these ideas is rather straightforward. Given the information on the external particles contributing to the process, we associate color labels of the form  $(i, \sigma_i)$ , depending on their flavor. The Feynman rules to build up the higher level subamplitudes, are the ones described above. The result, for each permutation, is a new colored ordered  $\mathcal{A}$ -function that corresponds to the given color factor  $\mathcal{F}_I$ . The computational cost is again given, as in the case of Berends-Giele recursive equations, by  $n^4$ . The total color-summed squared amplitude is obtained after summing over all  $n_l!$  color connection configurations using the color matrix  $\mathcal{C}$ .

In the generation of unweighted events a color connection information is needed for a proper matching with parton shower algorithms. For the selection of the color connection structure to be assigned to a given event we consider only those  $\mathcal{A}$ -functions that correspond to color connections without a 'neutral' gluon involved. The choice is based then on a probability distribution defined by

$$P_I = \frac{|\mathcal{A}_I|^2}{\sum_J |\mathcal{A}_J|^2}, \quad P_I > 0, \quad \sum_I P_I = 1$$

where  $I, J$  run over all color connections considered.

## 2.4 Interfacing and matching to parton shower programs

HELAC-PHEGAS generates a Les Houches Accord (LHA) file [33, 34] in a completely automatic way, with all the necessary information needed to interface to PYTHIA and/or HERWIG parton shower and hadronization programs.

Possible problems of double counting of jets may arise when interfacing fixed order tree level matrix elements to parton shower codes. The reason is that a jet can appear both from relatively hard emission during shower evolution or from inclusion of higher order matrix elements. In order to deal with this problem a matching or merging algorithm has to be applied. It removes double counting of jet configurations and provides a smooth transition between the part of the phase space covered by parton showers and the one described by matrix elements. We refer to [38–43] for a detailed account of these algorithms. Here we will briefly present what has been incorporated in HELAC-PHEGAS, which is the so-called  $k_\perp$  reweighting algorithm based on the  $k_\perp$  measure [44, 45]. Moreover, we will also give a brief description of the whole framework, within the so-called MLM matching approach [42], which goes beyond HELAC-PHEGAS capabilities and relies on the interface with a parton shower algorithm.

The matching algorithm can be described as follows:

1. At the beginning one generates all parton level configurations for all final state parton multiplicities  $n$  up to a given  $N$ . Due to the presence of collinear and soft singularities one has to use a set of *parton level* kinematical cuts:

$$p_T^{part} > p_T^{min} , \quad |\eta_{part}| < \eta_{max} , \quad \Delta R_{jj} > R_{min} , \quad (13)$$

where  $p_T^{part}$  and  $\eta_{part}$  are the transverse momentum and pseudorapidity of the final state partons, and  $\Delta R_{jj}$  is their minimal separation in the  $(\eta, \phi)$  plane. The parameters  $p_T^{min}$ ,  $\eta_{max}$  and  $R_{min}$  are called generation parameters, and are the same for all  $n = 1, \dots, N$ .

2. During the generation of events, the renormalization scale (running  $\alpha_s$ ) is set according to the CKKW prescription [38, 39]. To this end a tree branching structure is defined for each event, allowing, however, only for those branchings which are consistent with the color structure of the event. In HELAC-PHEGAS this is inherent in the matrix element calculation. More precisely for a pair of final-state partons  $i$  and  $j$ , we use the  $k_\perp$ -measure defined by

$$k_{\perp,ij} = \Delta R_{ij} \min(p_{Ti}, p_{Tj}) ,$$

where  $\Delta R_{ij} = \sqrt{\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2}$ , while for a pair of initial/final state partons we have  $k_\perp^2 = p_T^2$ , i.e. the  $p_T$  of the final state parton.

Then if  $k_{\perp,ij}^2$  is minimal the 'partons' are clustered, and the resulting 'parton' is again classified as a final state parton with  $p = p_i + p_j$  and adjusted flavor and color flow. In the case when incoming and outgoing partons are clustered, the new 'parton' is considered as incoming and its momentum is given by  $p = p_j - p_i$ . As a result we obtain a chain of  $k_{\perp}$ -measures. For every node, a factor of  $\alpha_s(k_{\perp,\text{node}}^2)/\alpha_s(Q_{\text{hard}}^2)$  is multiplied into the weight of the event. For the un-clustered vertices as well as for the scale used in the parton density functions, the hard scale of the process  $Q_{\text{hard}}^2$  is used. No Sudakov reweighting is applied.

3. At this level, an LHA file has been created, which can be processed independently for showering and hadronization. In that sense HELAC-PHEGAS involvement ends here. In order to have a self-contained presentation for the reader, we will now give a brief description of a possible matching algorithm related to the parton-showered events we have already used in Ref. [43]. For all partons resulting from the shower evolution a jet cone algorithm is applied. The resulting jets are defined by  $E_{T\text{min}}^{\text{clus}}$ ,  $\eta_{\text{max}}^{\text{clus}}$  and by a jet cone size  $R_{\text{clus}}$ . The parton from the parton-level event is then associated to one of the constructed jets. Starting from the parton with the highest  $p_T$  we select the closest jet ( $1.5 \times R_{\text{clus}}$ ) in the pseudo-rapidity/azimuthal-angle space. All subsequent partons are matched iteratively to jets. If this is impossible, the event is rejected. Additionally, for  $n < N$ , matched events with the number of jets greater than  $n$  are rejected, whereas for  $n = N$ , i.e. the highest multiplicity, events with extra jets are kept, only if they are softer than the  $N$  matched jets. This procedure provides the complete inclusive sample. The harder the threshold for the transverse energy of the jets used in the matching,  $E_T^{\text{clus}}$ , the fewer the events rejected by the extra-jet veto (i.e. smaller Sudakov suppression), which means that the role given to the shower approximation in the production of jets is more dominant. On the other hand using a lower threshold the role of the matrix-element calculation is enhanced, which can be seen as equivalent to a more substantial Sudakov suppression, reducing thus the role of the parton shower algorithm in the production of the inclusive sample.

In the current version, HELAC-PHEGAS 1.2.0, the  $k_{\perp}$ -reweight algorithm described so far is included and it can be applied (optionally) to all processes. Moreover, the hard scale of the process can be defined by the user in the `getqcdscale.h` file as described in the next section.

## 3 Running the code

### 3.1 Description of the code

The basic structure of the program is already described in [9]. Just to summarize, the program reads several input variables and in the so called *first phase*<sup>1</sup> the solution to the Dyson-Schwinger equations is constructed. In contrast to other programs all necessary information is kept in memory, no extra subdirectories are generated or needed<sup>2</sup>. This is the reason why HELAC-PHEGAS has a really compact and small source directory. All arithmetics in the *first phase* is completely integer and results in the construction of what we call a skeleton, a solution of the recursive equations. In the *second phase* based on the information produced so far, the program generates *completely automatically* phase space points by PHEGAS, and then calculates the corresponding matrix elements, for each color connection configuration separately. In this way not only the total weight can be computed but also the weight of each color connection configuration is available for free. Color and phase space un-weighting is therefore straightforward.

HELAC-PHEGAS incorporates all Standard Model particles and couplings in both unitary and Feynman gauges. Unstable particles are treated in a fully consistent way, either by including a fixed width or by using the complex mass scheme [46–48]. Moreover, when final states are considered, all correlations (spin, color) are automatically taken into account with no approximation involved.

### 3.2 Preliminary operations

Unpacking the code with the command

```
tar zxvf helac_1.2.0.tar.gz
```

will create the directory `helac_1.2.0`.

The program makes use of the Les Houches Accord PDF Interface library (LHAPDF). If this library is not installed on your machine, download it from <http://projects.hepforge.org/lhapdf/> and follow the installation instructions<sup>3</sup>.

After that you have to edit once for all the file `myenv`. Here you have to set up the following environmental variables:

**FC** is your FORTRAN compiler; nowadays `gfortran` is freely available and can be downloaded from <http://gcc.gnu.org/wiki/GFortran>. The code has been also tested with other compilers, like Lahey Fujitsu `lf95`, Intel Fortran `ifort` and GNU `g95`<sup>4</sup>.

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<sup>1</sup>By default both first and second phases are executed in one run.

<sup>2</sup>There is, however, the option to keep this information in a file and use it later on as well.

<sup>3</sup>Note that if you do not have root privileges, you can install the library in a local directory.

<sup>4</sup>The following compilers are available at `lxplus@cern.ch`: `gfortran`, `lf95` and `g95`.

`FORTRAN_LIBRARIES` is the name of the directory in which your FORTRAN libraries are located; in some cases they are automatically found by the compiler, and you do not need to write them explicitly;

`LHAPDFLIB` is the absolute path of your Les Houches Accord PDF Interface library; in a standard installation of LHAPDF, it is `/usr/local/lib`;

`LHAPDFSETS` is the absolute path of the directory in which the PDF sets are stored; in a standard installation of LHAPDF, it is `/usr/local/share/lhapdf/PDFsets`.

In case LHAPDF is not available HELAC-PHEGAS can still run in standalone mode (see below the definition of the `lhpdf` keyword) using the CTEQ6L1 best fit (LO fit with LO  $\alpha_s$ ). In both cases a running  $\alpha_s$  is available (LHAPDF provides its own running  $\alpha_s$ ).

### 3.3 How to run a process

The user interface consists of the following files:

`run.sh` is a bash script that reads the input files, compiles HELAC-PHEGAS and runs it. `run_lsf.sh` and `run_lsf2.sh` are its variants to run with the LSF system<sup>5</sup>.

`default.inp` contains a list of keywords, their default values and a short comment. The user should not modify this file, but use it just as a reference.

`keywords.list` is a list of all the available keywords; it is needed by `run.sh`.

`user.inp` is the only file that the user needs to edit. Here the user can select the process and modify the default values of many parameters.<sup>6</sup>

`getqcdscale.h` this is the file where the definition of the QCD scale to be used in the structure function as well as in the  $\alpha_s$  can be set *by the user*. By default (no editing is required) it will use  $Q_{\text{hard}} = M_Z$ .

`sub_lsf` and `sub_lsf2` are the bash scripts that send the jobs to the LSF system.

Let us now illustrate the structure of `user.inp` with an example.

```
# Compulsory information
colpar 1          # colliding particles: 1=pp, 2=ppbar, 3=e+e-
inist  3 -3       # initial state; enter 0 to sum over initial states
finst  11 -11     # final state
energy 14000      # collision energy (GeV)
```

---

<sup>5</sup><http://batch.web.cern.ch/batch/>

<sup>6</sup>The user is free to rename this file. We will refer to it as `user.inp` in the following just for clarity.

```
# For reference, here is the particle numbering:
# ve e u d vm mu c s vt ta t b photon z w+ w- g h f+ f- chi jet
# 1 2 3 4 5 6 7 8 9 10 11 12 31 32 33 34 35 41 42 43 44 100
# The respective antiparticles have a minus sign (for example: positron is -2)
# A jet in the final state is denoted by the number 100
```

```
# Enter here your additional commands if you wish to alter the default values
```

With the first four keywords we select the process we want to run and the collision energy. In the example, we run  $u\bar{u} \rightarrow t\bar{t}$  as part of a proton-proton collision at 14 TeV.

Entering two initial state particles with the `inist` keyword, we have implicitly chosen the *single process mode* of HELAC-PHEGAS. The other possibility is the *summation mode*, where the initial state particles are hadrons ( $pp$  in the example). HELAC-PHEGAS will find all the partonic processes that produce the selected final state and will sum over them. To achieve this, the user should replace the third line in the example with

```
inist 0          # initial state; enter 0 to sum over initial states
```

In this example, HELAC-PHEGAS finds 9 partonic subprocesses that produce  $t\bar{t}$  in the final state (i.e. the partonic initial state can be  $q\bar{q}$  and  $\bar{q}q$  for  $q = u, d, s, c$ , and  $gg$ ). The  $b$  quark, by default, is not taken into account as an initial state parton, but this can be changed with the `qnum` keyword which defines the number of quark flavors considered in the initial and final state, as described in the next subsection.

The summation over partonic subprocesses can also be performed in the final state. The particle identification ID=100 which we call a 'jet' has the following meaning: the programme will automatically find all parton level subprocesses, replacing this ID=100 with either a gluon or a quark (anti-quark). Which quark flavors are taken into account in this subprocesses generation is again defined by the `qnum` keyword. For example, if we replace third and fourth line in the example with

```
inist 0          # initial state; enter 0 to sum over initial states
finst 11 -11 100 # final state
```

HELAC-PHEGAS will look for all partonic subprocesses having  $t\bar{t} + 1$  parton in the final state. By default, the  $t$  quark is not taken into account as a 'jet' initiator.

In summation mode, the programme calls two auxiliary scripts, `script.sh` and `script.1.sh`, located in the `Summation_Processes` subdirectory.

In case of many jets in the final state, the number of subprocesses increases rapidly. Since the generation for different subprocesses is independent, the program is trivially parallelizable. As an example, we have implemented suitable scripts using the LSF system at `lxplus@cern.ch`, see subsection 3.5 for more details.

There are many parameters and options that can be changed by the user. All of them are listed in the `default.inp` file and described in more detail in subsection 3.4.

For example, the line of `default.inp` referring to the number of Monte Carlo iterations is

```
nmc 100000          # number of montecarlo iterations (single mode)
```

To change the number of Monte Carlo iterations from 100000 to let say 500000 one has to add the line

```
nmc 500000
```

at the end of the `user.inp` file. Choices made here will overwrite the default values.

After editing the `user.inp` file, you can compile and run the program by typing

```
./run.sh user.inp
```

or

```
./run.sh user.inp myenv-xxx.
```

In this last case, a file `myenv-xxx` will be use instead of `myenv`.

Summarizing, the user can edit `user.inp` but is not allowed to change its structure. In the upper part of the file (lines 1-13) the only thing the user can do is changing the numerical values of the first four keywords to select the process. In the lower part of the file (starting from line 14) the user can

1. Add lines in the form `keyword value` to alter the default values;
2. Add empty lines or comment lines.

In case of wrong keywords, repeated keywords or invalid values, the script will complain and ask the user if she/he wants to continue anyway.

## 3.4 Keywords explanation

### 3.4.1 Compulsory keywords

The following keywords must be present in each `user.inp` file (lines 2-5) in order to select a process which should be run. The symbols, *s*, *n*, *b* and *x* correspond to the string, integer, boolean (logical) and real data types respectively.

- **colpar** *n*: Colliding particles.  
Set to  $n = 1$  for a  $pp$  collision,  $n = 2$  for  $p\bar{p}$ ,  $n = 3$  for  $e^+e^-$ .
- **inist**  $n_1 n_2$ : Particles in the initial state.  
This keyword implicitly selects the running mode. If both  $n_1$  and  $n_2$  are chosen from Table 1, HELAC-PHEGAS will run in *single process mode*. If  $n_1 = 0$  and  $n_2$  is omitted, HELAC-PHEGAS will run in *summation mode*.

- **finst**  $n_1 n_2 \dots n_k$ : Particles in the final state.  
Allowed values are the numbers listed in Table 1. In summation mode,  $n_i = 100$  represents a jet.
- **energy**  $x$ : Collision energy in GeV.

### 3.4.2 Optional keywords

The following keywords allow the user to change many default parameters and options. They can be entered beginning from the 14th line of `user.inp`.

#### General options

- **exec**  $s$ : Name of the executable file to be produced.  
Default name is `helac-phegas.exe`.
- **outdir**  $s$ : Name of the output directory.  
Default name is `RESULTS`.
- **nglu**  $n$ : Number of gluons in the final state.  
In summation mode and with jets present in the final state, select only the subprocesses having  $n$  gluons in the final state. Set to  $n = -1$  to not constrain the number of gluons in the final state.  
Default value is  $-1$ .
- **qnum**  $n_1 n_2$ : Number of quark flavors in the initial and final state.  
In summation mode, when looking for the allowed subprocesses HELAC-PHEGAS will take into account only the  $n_1$  lightest flavors in the initial state, and the  $n_2$  lightest flavors as jet initiators in the final state.  
Default values are  $n_1 = 4$  ( $u, d, c, s$ ) and  $n_2 = 5$  ( $u, d, c, s, b$ ).
- **ktrw**  $b$ : Switch for the  $k_\perp$  reweighting algorithm.  
See section 2.4 for more details. Set F, f or 0 to switch off the algorithm, or set T,

Number	Particle	Number	Particle	Number	Particle
1	$\nu_e$	8	$s$	33	$W^+$
2	$e^-$	9	$\nu_\tau$	34	$W^-$
3	$u$	10	$\tau^-$	35	$g$
4	$d$	11	$t$	41	$H$
5	$\nu_\mu$	12	$b$	42	$\phi_+$
6	$\mu^-$	31	$\gamma$	43	$\phi_-$
7	$c$	32	$Z$	44	$\chi$

Table 1: Particle numbering



t or 1 to switch it on.

Default value is false.

- **lrgnc** *b*: Switch for large  $N_c$  limit.

In the limit  $N_c \rightarrow \infty$ , only the diagonal terms of the color matrix  $\mathcal{C}_{IJ}$ , cf. Eq. (11), survive, and all  $\mathcal{O}(N_c^{-2})$  terms are neglected. The interferences between different colour flows vanish which speeds up the calculation. This option can be used e.g. to test, whether the large  $N_c$  limit approximation can reliably describe the physical process<sup>7</sup>. Moreover, in the case when **ktrw** is switched on, the user still has the option to switch on or off the large  $N_c$  limit.

Default value is false.

- **error** *s*: Name of the file, where, every 1000 iterations, the cross section and its Monte Carlo error are recorded.

Default is **err\_file**.

- **gener** *n*: Choice of the phase space generator.

Besides the default PHEGAS [15] described in Section 2.1, there are two other possibilities. The first one is RAMBO [49], a flat phase-space generator. It generates the momenta distributed uniformly in phase space so that a large number of events is needed to integrate the integrands to acceptable precision, which results in a rather low computational efficiency. The second one is DURHAM, an algorithm that for a given order of the final state particles expresses the phase space in terms of the  $k_T$ ,  $\phi$  and  $\bar{y}$  variables, where  $\bar{y}$  is the difference of the rapidities of two nearest particles. Adaptation over all possible orderings of the final state particles is also included. For more details see Ref. [12]. Set to  $n = 0$  to use PHEGAS,  $n = 1$  for RAMBO or  $n = 2$  for DURHAM.

Default value is 0.

- **repeat** *n*: HELAC-PHEGAS run option.

Set to  $n = 0$  to run both phases of HELAC-PHEGAS,  $n = 1$  to run only the first phase, where the skeleton for a given process is constructed, or  $n = 2$  to run only the second phase.

Default value is 0.

- **ranhel** *n*: Choice of the set-up for the helicity configurations.

There are two possibilities, either exact summation over all helicity configurations is performed or Monte Carlo integration is applied [9]. For example for a massive gauge boson the second option is achieved by introducing the polarization vector

$$\varepsilon_\phi^\mu(p) = e^{i\phi} \varepsilon_+^\mu(p) + e^{-i\phi} \varepsilon_-^\mu(p) + \varepsilon_0^\mu(p), \quad (14)$$

---

<sup>7</sup>Let us stress here, that default calculation in HELAC-PHEGAS takes into account the full color structure, no approximation is involved.

where  $\phi \in (0, 2\pi)$  is a random number. By integrating over  $\phi$  the correct sum over helicities is obtained

$$\frac{1}{2\pi} \int_0^{2\pi} d\phi \, \varepsilon_\phi^\mu(p) (\varepsilon_\phi^\nu(p))^* = \sum_{\lambda=\pm} \varepsilon_\lambda^\mu(p) (\varepsilon_\lambda^\nu(p))^*.$$

The same idea is applied to the helicity of (anti)fermions. Set to  $n = 0$  to calculate explicitly all helicity configurations or  $n = 1$  to do a Monte Carlo over helicities.

Default value is 1.

- **alphasrun**  $n$ : Switch for the running of  $\alpha_s$ .  
Set to  $n = 0$  to have a fixed value of  $\alpha_s$  or  $n = 1$  to have a running coupling  $\alpha_s(Q^2)$ . In the later case the  $Q$  scale has to be implemented by the user in the `getqcdscale.h` file, where a few examples have already been provided.  
Default value is 0.
- **gauge**  $n$ : Choice of the gauge.  
Set to  $n = 0$  for the Feynman gauge or  $n = 1$  for the unitary gauge.  
Default value is 1.
- **ihiggs**  $b$ : Switch for the inclusion of the contribution coming from the Higgs boson.  
Default value is false.
- **widsch**  $n$ : Scheme for the introduction of the width of  $W$ ,  $Z$  bosons as well as the top quark [46–48]. Set to  $n = 0$  for the fixed width scheme or  $n = 1$  for the complex mass scheme.  
Default value is 0.
- **qcd**  $n$ : Option for the type of interactions.  
Set to  $n = 0$  to have only electroweak interactions,  $n = 1$  to have both electroweak and QCD and  $n = 2$  for QCD only.  
Default value is 1.
- **unwgt**  $b$ : Switch for the un-weighting procedure.  
If set to false events are not unweighted. If set to true events are unweighted.  
Default value is true.
- **preunw**  $n$ : Pre-unweighted events.  
Number of events generated to calculate the maximal weight to start the un-weighting procedure. It is recommended that the user tries different values in order to obtain a better un-weighting efficiency.  
Default value is 10000.
- **unwevt**  $n$ : Number of unweighted events to be generated.  
In the summation mode,  $n$  is the total number of unweighted events, which is

distributed between all possible parton level processes according to their relative contribution to the total cross section.

Default value is 50000.

- **nmc**  $n$ : Number of Monte Carlo iterations in the single process mode.  
Not used in summation mode.  
Default value is 100000.
- **nmc1**  $n$ : Number of Monte Carlo iterations in the first step of the summation mode.  
Not used in single process mode.  
Default value is 100000.
- **nmc2**  $n$ : Number of Monte Carlo iterations in the second step of the summation mode. Not used in single process mode or if un-weighting is switched off.  
Default value is 3000000.
- **optim**  $n_1 n_2 n_3 n_4 n_5 n_6$ : Optimization options for the PHEGAS phase space generator. Optimization is performed when the program reaches the Monte Carlo iterations

$$\left\{ o_1 = n_1, o_2 = o_1 + n_2 n_3, o_3 = o_2 + n_2 n_3^2, \dots, o_{n_4} = o_{n_4-1} + n_2 n_3^{n_4-1} \right\}.$$

It stops when the maximum number of optimizations  $n_4$  is reached, or when the  $n_5$ -th Monte Carlo iteration is reached.  $n_6$  is a flag: if set to 0 optimisation is not performed, if set to 1 it is performed.

Default values are 10000 10000 1 8 100000 1.

- **lhpdf**  $b$ : Switch for the use of the Les Houches Accord PDF interface library.  
If set to F, HELAC-PHEGAS will run in standalone mode, using the CTEQ6L1 best fit (LO fit with LO  $\alpha_s$ ).  
Default value is false.
- **pdf**  $n$ : Choice of the PDF set.  
Used only if **lhpdf** is set to true.  $n$  must be equal to the LHAGLUE number of the desired PDF set (see PDFsets.index or Ref. [28]). Enter  $n = 0$  to run without PDFs.  
Default value is 10042, which corresponds to CTEQ6L1 (LO fit with LO  $\alpha_s$ ).
- **pythia**  $n_1 n_2$ : IDWTUP and NPRUP parameters for the LHA sample files.  
IDWTUP dictates how the event weights are interpreted by the showering and hadronization event generators. NPRUP is the number of different user processes, see [33] for more details.  
Default values are  $n_1 = 3$ , which corresponds to an option with unweighted events with the weight = +1, and  $n_2 = 1$ , which corresponds to the one process only.

- **constants  $b$ :** if  $b = 1$  the user can provide its own `constants.h` file in accordance to the prototype given in the `constants_std.h` file.

Default value is  $b = 0$ , see below the description of physical constants.

### **pp(bar) cuts<sup>8</sup>**

The following options are read only if `colpar` is set to 1 or 2 (respectively,  $pp$  and  $p\bar{p}$ ). All dimensional quantities are in GeV. When the word 'quark' appears, light quarks and gluons have to be understood.

keyword	description	default
<code>cutoffp <math>x</math></code>	Cutoff value	1.0d-3
<code>minptl <math>x</math></code>	Minimum lepton $p_T$	1.0d-3
<code>minptq <math>x</math></code>	Minimum quark $p_T$	8.0
<code>minptb <math>x</math></code>	Minimum bottom $p_T$	8.0
<code>minptt <math>x</math></code>	Minimum top $p_T$	0.0
<code>minptp <math>x</math></code>	Minimum photon $p_T$	8.0
<code>maxrapl <math>x</math></code>	Maximum lepton rapidity	10.0
<code>maxrapq <math>x</math></code>	Maximum quark rapidity	2.0
<code>maxrapb <math>x</math></code>	Maximum bottom rapidity	2.0
<code>maxrapt <math>x</math></code>	Maximum top rapidity	10.0
<code>maxrapp <math>x</math></code>	Maximum photon rapidity	2.0
<code>mindrll <math>x</math></code>	Minimum $\Delta R$ separation between lepton and lepton	0.0
<code>mindrlq <math>x</math></code>	Minimum $\Delta R$ separation between lepton and quark	0.0
<code>mindrqq <math>x</math></code>	Minimum $\Delta R$ separation between quark and quark	0.7
<code>mindrqb <math>x</math></code>	Minimum $\Delta R$ separation between quark and bottom	0.7
<code>mindrbb <math>x</math></code>	Minimum $\Delta R$ separation between bottom and bottom	0.7
<code>mindrpf <math>x</math></code>	Minimum $\Delta R$ separation between photon and fermion	0.0
<code>minmqqp <math>x</math></code>	Minimum quark-quark invariant mass in the $pp/p\bar{p}$ case	0.0
<code>minmqb <math>x</math></code>	Minimum quark-bottom invariant mass	0.0
<code>minmbb <math>x</math></code>	Minimum bottom-bottom invariant mass	0.0

### **$e^+e^-$ cuts<sup>9</sup>**

The following options are read only if `colpar` is set to 3 ( $e^+e^-$ ). All dimensional quantities are in GeV.

---

<sup>8</sup>Cuts not already provided may be added in the `2.cuts_auto_pp.f` file.

<sup>9</sup>Cuts not already provided may be added in the `2.cuts_auto_ee.f` file.

keyword	description	default
<code>cutoffe x</code>	Cutoff value	1.0d-3
<code>minenl x</code>	Minimum lepton energy	10.0
<code>minenq x</code>	Minimum quark energy	10.0
<code>minenp x</code>	Minimum photon energy	10.0
<code>minanglb x</code>	Minimum angle (degrees) between lepton and beam	5.0
<code>minangqb x</code>	Minimum angle (degrees) between quark and beam	5.0
<code>minangpb x</code>	Minimum angle (degrees) between photon and beam	5.0
<code>minangll x</code>	Minimum angle (degrees) between lepton and lepton	5.0
<code>minanglq x</code>	Minimum angle (degrees) between lepton and quark	5.0
<code>minangqq x</code>	Minimum angle (degrees) between quark and quark	5.0
<code>minangpf x</code>	Minimum angle (degrees) between photon and fermion	5.0
<code>minmqq x</code>	Minimum quark-quark invariant mass in the $e^+e^-$ case	10.0

### Physical constants

The user can set the values of many physical constants using the keywords reported in Table 2.

By default the electroweak couplings are given by

$$\sin^2\theta_w = 1 - \left(\frac{m_W^2}{m_Z^2}\right), \quad g_{weak} = (4\sqrt{2}G_F)^{1/2}m_W, \quad \alpha_{em} = \sqrt{2}G_F m_W^2 \sin^2\theta_w / \pi$$

However, the user can optionally give values for  $\alpha_{em}$  (`alphaem`) and  $\sin^2\theta_w$  (`sin2thetaw`).

For more advanced users, it is recommended to edit and provide their own `constants.h` file. A prototype is included, see the `constants_std.h` file. The CKM [50, 51] matrix is also possible to be defined in this file, as well as masses and widths for all particles.

### 3.5 How to run HELAC using the LSF system

Running HELAC-PHEGAS on a single machine can become impractical when the final state contains many particles and jets, either because of time constraints or because of the amount of output that can be produced. A possible solution to this problem is to run the  $n$  involved subprocesses at the same time on a computer cluster. We provide scripts to run HELAC-PHEGAS on the CERN's batch system

The keywords `queue1` and `queue2` allow the user to choose the queue for the subprocesses in the first and second phase of the HELAC-PHEGAS run.

By default, jobs are sent to the `8nm` queue, 8 minutes, which is suitable only for short runs. Two options are available:

1. Write everything, also the intermediate files, which can be quite large, in the AFS area.

In this case, a `user.inp` file has to be prepared as usual, and then

keyword	description	default
<code>gfermi x</code>	Fermi coupling constant	1.16639d-5
<code>sin2thetaw x</code>	Sinus squared of Weinberg angle $\sin^2\theta_w$	-1*
<code>alphaem x</code>	Electromagnetic coupling constant	-1*
<code>alphas2 x</code>	Fixed strong coupling constant, used only if <code>alphasrun</code> is 0	0.118
<code>zmass x</code>	$Z$ mass	91.188
<code>zwidth x</code>	$Z$ width	2.446
<code>wmass x</code>	$W$ mass	80.419
<code>wwidth x</code>	$W$ width	2.048
<code>higmass x</code>	Higgs boson mass	130.0
<code>higwidth x</code>	Higgs boson width	4.291d-3
<code>emass x</code>	$e$ mass	0.0
<code>mumass x</code>	$\mu$ mass	0.0
<code>taumass x</code>	$\tau$ mass	0.0
<code>umass x</code>	$u$ quark mass	0.0
<code>dmass x</code>	$d$ quark mass	0.0
<code>smass x</code>	$s$ quark mass	0.0
<code>cmass x</code>	$c$ quark mass	0.0
<code>bmass x</code>	$b$ quark mass	0.0
<code>tmass x</code>	$t$ quark mass	174.3
<code>twidth x</code>	$t$ quark width	1.6

Table 2: Keywords and default values regarding some physical constants.

\*The value  $-1$  for the keywords `sin2thetaw` and `alphaem` means that they are defined as described in the text.

`./sub_lsf`

should be run. The user will be asked to provide some information like job name, queue, user input file and environment file. The queue will only be used for the controller job, and may, therefore, be short.

## 2. Write everything on the remote, `1xb`, hosts (suggested method).

At the end of the run, the sample will be written in the AFS directory from which the job has been submitted. The usual output directory will be written, in compressed form, in the user's personal CASTOR area.

Similarly to the previous case, a `user.inp` file has to be prepared and then

`./sub_lsf2`

should be run. The user has to provide a job name, queue, user input file and environment file. The script will automatically resubmit a job to a longer queue, if

it failed. Notice, however, that this is only useful in the case of a failure due to time constraints.

There are two reasons for using this method:

1. To save time. More subprocesses run at the same time, while with the standard procedure they run one after the other.
2. To save space. The output files produced can exceed your disk quota.

The first procedure (`sub_1sf`) saves time but not space, whereas the second one (`sub_1sf2`) saves also space. Another reason to prefer the second procedure is the automatic resubmission of failed jobs, which only is implemented in this case.

## 3.6 Description of the output

All the outputs produced by the HELAC-PHEGAS program will be written in a subdirectory, whose name is defined by the keyword `outdir`. Let us distinguish two main cases.

### 3.6.1 Single process mode

In the output directory you will find the following files.

- Executable files. The HELAC-PHEGAS executable (whose name is defined by the keyword `exec`) and, only if `unwgt` is true, the executable for the un-weighting procedure, `unwei.exe`.
- User input file, called `user.inp` throughout this paper.
- `input_sp` and `output`. Respectively input and output redirected files of the HELAC-PHEGAS executable. If `unwgt` is true, the output of `unwei.exe` is appended to `output`.
- The error file, whose name is defined by the keyword `error`. Every 1000 iterations, the cross section and its error are recorded to this file. The three columns are respectively the number of iterations, the cross section and the error.
- The kinematic file, `kine_XXX.out`, where `XXX` represents the process. Used for debugging.
- The event sample file, `sampleXXX.lhe`, where `XXX` represents the process, in the standard format dictated by the Les Houches accord [33,34]. It is generated only if `unwgt` is set to true.

### 3.6.2 Summation mode

In the output directory you will find

- The HELAC-PHEGAS executable.
- User input file.
- `infile`, the input file for `processes.f`, that generates all the subprocesses.
- The (gzipped) sample file, `sampleXXX.lhe.gz`, where `XXX` describes the final state. It is generated only if `unwgt` is set to true.
- A subdirectory 1, where all the outputs generated in the first phase, generation of weighted events, will be written.
- A subdirectory 2, where all the outputs generated in the second phase, generation of unweighted events, will be written. It is generated only if `unwgt` is set to true.

The subdirectory 1 contains

- `input`, a skeleton of input files, needed to generate the real input files for each single subprocess.
- `output`, the output of `readoutput.f`.
- `results.output`. Each group of two lines refers to a single subprocess. The first line is the cross section and the second is the error.
- `cross_sections`. The  $n$ -th line shows the percentage of the total cross section represented by the  $n$ -th subprocess.
- Subdirectories `directory_n`, one for each subprocess. The content of each of these directories resembles the one described for the single process mode, except that most of the files are gzipped to save space.

The content of the subdirectory 2 is analogous to 1, with the main exception that in the `results.output` file a third and a fourth line for each subprocesses is added, showing information on generated unweighted events.

### 3.6.3 Output of the main HELAC-PHEGAS executable

A substantial part of the information contained in the output of `helac-phegas.exe` is self-explainable. In this section we would like to make the user familiar with the main points of this file. Lets take as the basic example the following process  $u(p_1)\bar{u}(p_2) \rightarrow g(p_3)g(p_4)$ .

The output file begins with the reproduction of the input file, followed by masses and widths of all SM particles. Then we have



```

QCD INCLUDED, g= 1.217715784776720 0.11800000000000000
UqUaGOG0
TIME= 2007 10 8 180 19 26 52 966
avhel,avcol,symet
0.25000000000000000 0.11111111111111111 0.50000000000000000

```

where the process is clearly stated `UqUaGOG0`, together with the QCD coupling and factors that correspond to the average over initial helicities, colors and the symmetry factor. Then the 'first phase' starts. For each color connection configuration the color connection assignments for all particles is given, namely

```

the colour of particles ONE 2 0 3 1
the colour of particles TWO 0 1 2 3

```

the first line is the color connection the second the anti-color one (kept fixed at the ordinal permutation). Then the solution for the Dyson-Schwinger equations is presented in the following form

```

for the      3      2 colour conf. there are      8 subamplitudes
  1  2  6 -3  5  1  1  4 35  3  2 -3  2  0  0  0  1  1  1
  2  2  6 -3  5  0  1  4 35  3  2 -3  2  0  0  0  2  1  1
  3  2 10 -3  6  1  1  8 35  4  2 -3  2  0  0  0  1  1  3
  4  2 10 -3  6  0  1  8 35  4  2 -3  2  0  0  0  2  1  3
  5  2 14 -3  7  1  2  4 35  3 10 -3  6  0  0  0  1  1  1
  6  2 14 -3  7  0  2  4 35  3 10 -3  6  0  0  0  2  1  1
  7  2 14 -3  7  2  2  8 35  4  6 -3  5  0  0  0  1  1  3
  8  2 14 -3  7  0  2  8 35  4  6 -3  5  0  0  0  2  1  3

```

Let us focus on the line number one

```

  1  2  6 -3  5  1  1  4 35  3  2 -3  2  0  0  0  1  1  1

```

It simply encodes all information – to be used internally – corresponding to the fusion of an  $\bar{u}$  with momentum  $p_2$  with the  $g$  with momentum  $p_3$  to produce an  $\bar{u}$  with total momentum  $p_2 + p_3$  (all momenta taken incoming). At the end of this part a line with

```

the number of Feynman graphs = 3
the number of Feynman graphs = 3

```

followed by the color matrix is given. The number of Feynman graphs for this process is of course three. Then the number of channels to be used by PHEGAS (always the number of graphs +1) is given with the number of MC points `nmc` and optimization parameters.

```

Number of channels 4
Number of MC points

```

```

nmc    = 100000
nopt,nopt_step,optf,maxopt,iopt
100 10000 1.0000000000000000 8 1
number of channels= 4
NUMBER OF CHANNELS 4

```

Since PHEGAS is using Feynman graphs as the basic structure of the multichannel phase-space mappings, a description of each Feynman graph is given as follows:

```

the graph 1
14 -3 12 35 2 -3 0 0
12 35 4 35 8 35 0 0

```

After a few lines with self-explained information the cuts

```

-----
                the cuts
pt      of  3   particle  8.0000000000000000
energy of  3   particle  8.0000000000000000
pt      of  4   particle  8.0000000000000000
energy of  4   particle  8.0000000000000000
rapidity of  3   particle  2.0000000000000000
rapidity of  4   particle  2.0000000000000000
cos-beam1 of  3   particle  0.9640275800758169
cos-beam1 of  4   particle  0.9640275800758169
cos-beam2 of  3   particle  0.9640275800758169
cos-beam2 of  4   particle  0.9640275800758169
DR      3   with  4 0.7000000000000000
cos of  3   with  4 0.7648421872844885
mass of  3   with  4 5.486364919287221
-----

```

applied are given for each particle or pair of particles. Then a bunch of lines follows in the form

```

sigma=  0.175490D+03   0.709135D-01       491       1000       1000
-----

```

where the calculated cross section `sigma` with the percentage error, the number of events passing the cuts, the number of phase-space points used as well as the number of phase-space points tried, is given.

At the end of the file one normally has

```

out of 100000 100001 points have been used
and 50419 points resulted to != 0 weight
whereas 49582 points to 0 weight
estimator x: 0.182757D+03
estimator y: 0.147435D+01
estimator z: 0.124416D-02
average estimate : 0.182757D+03
+ \- 0.121423D+01
variance estimate: 0.147435D+01
+ \- 0.352726D-01
lwri: points have used 0.0000000000000000E+00
2212 2212 7000.000000000000 7000.000000000000 3 1
% error: 0.6643944554436630

```

which is translated to the total cross section in nb 0.182757D+03 the MC error also in nb 0.121423D+01 and the percent error 0.6643944554436630%.

If the `unwgt` is set to true the distribution of the weights is plotted for the number of events given by `preunw`. Then the un-weighting procedure starts and the number of unweighted events is additionally printed. In case of un-weighting the final histogram of the weights is also printed.

### 3.7 External phase space points

In this mode the user can provide by herself/himself momenta for the particles participating in the process under consideration and get back information on the squared matrix element summed over spin and color degrees of freedom. Additionally, the color ordered amplitude for a given color connection and helicity configuration can be obtained.

- `onep`: Set to true in order to have the described option.  
Default value is false.
- `mom`: Name of the input file provided by the user with the momenta of the particles, in the format  $p_x, p_y, p_z, E, m, w$ , where  $w$  is a weight for phase space generation, usually set  $w = 1$ . A prototype is included under the name `mom`.  
Default name is `mom`.
- `momout`: Name of the output file.  
Default name is `momout`.

### 3.8 Benchmarks

From the physics point of view HELAC-PHEGAS has already been used in several contexts to produce results in physics. A few examples are: the Monte Carlo generator NEXTCALIBUR [52] that includes the EXCALIBUR [53] phase space generation and HELAC-PHEGAS

matrix elements, used in  $e^+e^-$  analysis; the extensive comparison with SHERPA on six-fermion production processes [54]; and more recently the participation in the  $W + n$  jets comparative study [43] of different Monte Carlo codes namely ALPGEN, ARIADNE, HELAC-PHEGAS, MADEvent and SHERPA.

On the technical side, we provide a number of benchmark calculations in the web-page of the code, so that the potential user can test and validate his own results.

## 4 Outlook

The current version is named 1.2.0; it is meant to be publicly used: in that sense we welcome any bug report or simple question. The first number introduces major changes, the first one described below. The second number refers to minor changes and/or additions, whereas the last one to bug corrections.

A version with all Higgs-gluon and Higgs-photon couplings, in the large  $m_{top}$  limit will follow as 1.3.0. It is already tested and will be available soon on the HELAC-PHEGAS web-page.

A new version suitable for processes with many colored particles, i.e. with a number of equivalent gluons more than 9, for instance  $gg \rightarrow 8g$  and more, has been already developed and tested [12]. It will be incorporated in version 2.

We are also working on the inclusion of MSSM particles and couplings.

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